STUDY OF THE DECAY AND RECOVERY OF ORBITING ARTIFICIAL SPACE OBJECTS

Grant NGR 09-015-007

Final Report

For the period 1 December 1965 to 30 June 1971

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National Aeronautics and Space Administration
Washington, D.C. 20546

Smithsonian Institution
Astrophysical Observatory
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ABSTRACT

The reentry of earth-orbiting space objects unconsumed in the atmosphere represents a potential hazard to populated areas of the earth. Since the mid-1950s, the Smithsonian Astrophysical Observatory has conducted a program called Moonwatch, whose purposes were to observe orbiting artificial satellites and reentries of space objects and, if possible, to recover and analyze reentered pieces. In addition, through observations of low-perigee objects, data obtained by Moonwatchers have been instrumental in defining some of the factors affecting satellite decay.

This final report documents the results of the "Study of the Decay and Recovery of Orbiting Artificial Space Objects" performed under Grant NGR 09-015-007 for the National Aeronautics and Space Administration as part of the Moonwatch program.

The background leading up to this grant and the operations and procedures of the Moonwatch Network are outlined. The objectives of the program are presented, and the problems that enter into satellite-orbit and decay predictions are addressed. Moonwatchers contributed substantially to increasing an overall prediction capability, and some of the specific achievements over the 6-year period are cited. Although no major space fragments were recovered as a direct result of this program, most of its secondary goals were indeed accomplished.

The prediction accuracy improved during the grant period, but an uncertainty on the order of 10% still remains in the description of a final "decay window."

STUDY OF THE DECAY AND RECOVERY OF ORBITING ARTIFICIAL SPACE OBJECTS

Final Report

1. BACKGROUND

From the very beginnings of the space age, the problems of predicting both a satellite orbit decay and its subsequent point of impact on the earth have become of increasing concern, especially in light of the larger and more dense vehicles being launched by the United States and other countries and the potential hazards they represent on uncontrolled atmospheric reentry. Many pieces of space hardware actually survive burn-in, thus posing a threat if they should impact a populated area of the earth.

Partly out of this concern grew the Moonwatch Division of the Smithsonian Astrophysical Observatory (SAO), under the direction of Dr. Fred L. Whipple. The Moonwatch Division was initiated in 1956 as a result of the National Academy of Science and the National Science Foundation assigning responsibility to SAO for the optical tracking of United States artificial earth satellites during the International Geophysical Year. The Moonwatch Division was given responsibility for amassing data for this research effort, with related research to be conducted by SAO scientists within their respective disciplines. Moonwatch became a global network of visual observers, made up of amateur astronomers who volunteered their time to aid in tracking artificial earth satellites.

At a meeting of Moonwatch team leaders in Cambridge, Massachusetts, in May 1962, Whipple pointed out that since the decay of a satellite and its plunge to earth cannot be predicted with certainty, visual observations provided by Moonwatchers would be useful in determining the path of an object during its final hours of flight. A "deathwatch" for Sputnik 4 was organized in August, and nearly 750 observers were mailed detailed instructions for a reentry patrol.

In the early morning of September 5, atmospheric resistance caused the fiery descent of Sputnik 4 to earth over northeastern Wisconsin, with the accompanying brilliant display seen and heard by hundreds of people in the area. The most valuable observations of its breakup and descent were made by members of the Moonwatch team from the Milwaukee Astronomical Society. Indeed, later that morning, a 20-pound fragment was picked up by two Manitowoc, Wisconsin, policemen, who found it embedded in an asphalt road surface. This chunk, the first known piece of man-made debris ever to be recovered from orbit, was rapidly transported to SAO for analysis.

This incident was a key part in a succession of events leading to Grant NGR 09-015-007 from the National Aeronautics and Space Administration (NASA) for a "Study of the Decay and Recovery of Orbiting Artificial Space Objects." The primary purpose of this study was to observe reentries and to recover and analyze reentering pieces. Other objectives, described more fully in Section 2, included maximizing use of SAO's existing observing capabilities and developing computer programs for generating predictions more precisely and more rapidly.

If accurate predictions could be made of satellites in low orbits, with series of such predictions leading to a refinement of the method, it was hoped that the acceleration of orbital decay could be defined and that earth-impact locations could perhaps be predicted, enhancing the possibility of recovering satellite fragments for analysis.

It was felt that an empirical approach should be taken to help define the actual moment of satellite decay. In this empirical approach, a satellite decay would be observed by as many people as possible and the conditions of reentry recorded. Given information obtained from observations and photographs of visible portions of several reentries, investigators could estimate the decay trajectory and thus the time and place of earth impact. These data, in turn, could be used to improve the prediction program.

To secure these quantities of satellite-decay data, Moonwatch recruited a great number of volunteer observers worldwide, training them in a specially designed program to enable them to track reentering as well as orbiting satellites.

During the term of this grant, the Moonwatch Network encompassed more than 200 registered satellite-observing teams and over 200 cooperating professional and amateur astronomical observatories distributed on all continents except Antarctica. In addition to observing and searching for satellite decays and attempting to recover "lost" satellites, Moonwatchers have been tracking hundreds of satellites on a routine basis for use in various areas of related research. Within the period of this grant, Moonwatch has made over 300,000 positional and optical-signature observations.

In coordinating this satellite-tracking effort, Moonwatch worked with and was closely associated with the United States Air Force's NORAD Space Defense Center, Cheyenne, Wyoming, as well as with other satellite-tracking groups around the world, and, of course, with other SAO observing facilities.

SAO has been operating a worldwide network of Baker-Nunn camera (since 1957) and laser (since 1967) satellite-tracking stations under a separate grant from NASA. These stations have regularly been tasked within the terms of this Decay and Recovery grant, thereby providing many of the precise data utilized in research relating to atmospheric and geodetic studies necessary for the development and refinement of techniques for predicting satellite decays. In turn, the Moonwatch program has supplied important observational data to the Baker-Nunn network, especially in defining rough orbits for satellites temporarily lost by the Baker-Nunn cameras (as, for example, might happen if a newly launched satellite, through some malfunction, was not in its predicted orbit).

SAO also operates the Meteorite Recovery (Prairie) Network,[*] located in the central United States plains. This network of 16 stations, established to photograph meteors entering the earth's atmosphere, has provided Moonwatch with photographic data on the structure of the middle and lower atmosphere by recording meteoritic penetration of the atmosphere.

In 1965, the Volunteer Flight Officers Network (VFON), a type of "aerial" Moonwatch, was formed as a small group of pilots employed by United Airlines so that they could report atmospheric-entry phenomena to SAO. The organization grew and was finally brought under the direction of and has been wholly administered by the Moonwatch Division since January 1, 1969, under a continuing contract with the United States Air Force.[†] The VFON encompasses 118 airlines, representing 54 countries. Approximately 50,000 flight personnel, flying nearly 3 million unduplicated air miles, are involved in the reporting of atmospheric phenomena.

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[*]Supported by Grant NGR 09-015-033 from the National Aeronautics and Space Administration.

[†]Supported by Contract F05603-70-C-0215 from the United States Air Force.

2. OBJECTIVES

The Study of the Decay and Recovery of Orbiting Artificial Space Objects was undertaken for the purpose of observing, searching for, and recovering fragments of orbital launch vehicles, artificial satellites, and other re-entering bodies. Primary objectives were to understand better the parameters of uncontrolled satellite reentry and the survivability of unconsumed pieces, to observe reentries and determine the many factors affecting satellite decay, and, when possible, to recover and analyze reentered pieces.

In addition, the program was to study, evaluate, and develop methods for the maximum utilization of existing SAO observing capabilities — the Baker-Nunn, Moonwatch, and Meteorite Recovery Networks. This included developing new techniques to increase the probability of successfully recovering fragments and instructing network personnel in the application of new methods. This task also included the establishment of a select group of observers within the Moonwatch network who would use large-aperture telescopes to observe nontransmitting satellites at great distances.

Near-real-time communications were to be established between the various networks and the SAO computing center, with near-real-time computing services available for a period of several days preceding each predicted reentry. Rapid procedures would be developed and maintained, by computer or otherwise, for correcting predictions from observations. Routine two-way communications would be improved, resulting in a minimum of delay between SAO and field observers.

A computer program was to be developed for predicting satellite orbits immediately preceding decay and for predicting the time and place of reentry trajectories. It was also hoped that a refined spiral-decay program could be developed, a program that would consider, in addition to conventional atmospheric-drag effects, various gravitational effects, solar radiation pressure, and lunisolar perturbations.

All reentry locations and fragment-impact areas were to be reported to NASA Headquarters. On the advice and request of NASA, Moonwatch would then conduct searches, obtain photographs, and inform NASA of the size, weight, markings, and time and place of impact of any fragments found, as well as of any other pertinent data. It was also hoped that laboratory analyses of recovered objects could be conducted by SAO.

3. STRUCTURE AND OPERATIONS

The Moonwatch Division of SAO is a volunteer organization that has been effectively providing satellite-tracking and reentry data to NASA, Smithsonian, and other scientists around the world without interruption since 1956.

In the early days of satellite tracking, before even rough predictions could be made on satellite orbits, not much was known about where or when to look for a satellite. Therefore, to locate one required large numbers of observers, each covering only a small segment of the sky. The original concept of Moonwatch was to form "fences," teams of people, with each observer looking through a telescope at a small area of the sky along the meridian so that any object crossing this north–south fence would be seen by at least one observer. One additional person sat with a clock. As soon as an observer spotted a satellite, he or she informed the timekeeper, who immediately logged in the time, identification, and location. By the middle of the 1960s, computer orbit predictions had become sufficiently accurate that observers now knew when and where to look and individual Moonwatchers could handle what previously took a team. The team approach, however, has remained, largely through the desire of the Moonwatchers themselves.

The Chief of the Division, headquartered in Cambridge, Massachusetts, acts as liaison between the professional space-research investigators at SAO and NASA and the Moonwatchers in the field. He has been supported over the years by varying levels of staff. All observations made by Moonwatchers are sent to Cambridge, where the Chief prepares them for the computer. In turn, he sends newly calculated predictions out to the field.

In addition, the Moonwatch Chief is called on for special help from individual Moonwatchers, generally by phone or by mail. He advises them on any technical problems they might be having, such as adjusting a new telescope.

General ephemerides covering satellites of interest are mailed to all observers every 2 weeks, with ephemeris updates supplied for the intervening weeks. Detailed information is also provided by Headquarters for observing special objects or events, such as satellite reentries, manned space-flight missions, flashing satellites, weather and amateur radio satellites, and atmospheric tests.

When a satellite is about to decay, decay alerts are telegramed to Moonwatchers. About three or four such alerts occur each month, for which "miniephemerides" are generated, consisting of approximate times and angles. In the early days of manned orbital flights, special alerts were called on each such flight, and miniephemerides were again telegramed. Some of the communications for alerting observers to satellite reentries and special events are handled via amateur radio.

The first priority in choosing satellites to be tracked by Moonwatchers is to select those that provide the best opportunities for observations during and near decay. An equally concerted effort has been made over the years to observe certain low-perigee satellites on request from researchers.

During the later years of the grant, an additional classification of high-apogee satellites has been added to the priority list. These satellites, with average apogee and perigee heights of approximately 30,000 and 300 km, respectively, introduce further complications into the preparation of workable ephemeris predictions. Nearly 125 satellites in this category have been tracked by Moonwatchers.

On the priority list at any one time are usually about a dozen satellites to be tracked for SAO research, approximately 14 for the harmonic studies conducted by Dr. Desmond King-Hele of the Royal Aircraft Establishment in England, and about 70 at the request of NORAD. In particular, NORAD has sought Moonwatch observations of Molniya-type satellites. These Soviet objects are especially difficult to track because of their unusual orbits, approaching very close and rapidly to earth and then swinging way out and slowing down.

A satellite remains on the priority list until either it decays completely or the scientist or agency requesting the data no longer needs further observations.

The Moonwatch Division publishes a monthly Newsletter distributed to all members, in which are listed the satellites to be observed that month. It was originally intended as a training device and for motivational purposes; since the former became less necessary and the latter self-perpetuating, the Newsletter has evolved into more of a statistical document. In addition to technical and operational information and satellite-search and reentry data, the Newsletter includes current Smithsonian Responsibility satellites, satellites launched throughout the world that month, satellites decayed during the month, priority satellites for the month, and ephemerides on selected stable satellites. Special reports are included, such as contributed articles on astronomical events or reports by Moonwatchers of new ideas. The first Moonwatcher to observe a particular satellite is also cited in the Newsletter. Positional observations made during the month are listed by team, together with a summary of optical-signature observations.

Moonwatch also publishes the VFCN Satellite Reentry Newsletter, containing instructions for observing objects of interest. Distributed to all participating flight officers, the monthly Newsletter lists satellites expected to decay within the next 60-day period and the predicted dates. Satellites that decayed within the previous 30-day period are also given, together with their decay date, time, and location when possible. Statistics of all pilot reports received in the 30-day period are presented; this includes identification of the airline and reporting flight crew, the date, the time, the position and altitude of the airplane, the length and magnitude of the sighting, the identification of the object reported, and a description of the object.

4. INSTRUMENTATION AND EQUIPMENT

4.1 Moonwatch Telescopes

Satellite-tracking telescopes used by volunteer observers range from the conventional 5-inch objective (apogee) scope to large, 100-inch-diameter observatory telescopes.

The primary instrument used by observers is the Moonwatch telescope, a 20-power F/4 refractor with a field of view of $2\overset{\circ}{.}5$, modified from the elbow telescope following a design by Whipple. This apogee telescope is capable of reaching 9th-magnitude satellites under reasonable sky conditions and has been the mainstay for near-earth satellite tracking. Competent experienced observers have achieved standard deviations well under 2 arcminutes with this telescope, an accuracy comparable to Baker-Nunn field-reduced observations. This measure of accuracy, together with the high volume of Moonwatch observations, has provided researchers with many useful data.

Moonwatchers have also been able to call on a number of observatories with superior instrument capabilities for special observing tasks. Most of these facilities are capable of astrophotography (some with cooled emulsions), spectroscopy, and polarization photography. Several stations have electronic image-intensification equipment with amplification ratios of 100,000:1. Image intensifiers, coupled with telescopes with objectives of 16 inches or larger, are capable of optically recording satellite images as faint as 17th magnitude, thus allowing observations of objects in synchronous earth orbit, as well as some deep-space probes. In addition, the Moonwatch station in Dayton, Ohio, utilizing a specially designed four-axis satellite-tracking mount equipped for photoelectric photometry, can follow a satellite path from horizon to horizon, recording variable-magnitude satellite profiles that clearly show differences of tenths of a magnitude.

4.2 Prairie Network Camera

The Prairie Network camera is an F/0.8 Super-Schmidt system with a 200-mm focal length. The 16 unmanned, automatic camera stations extend from South Dakota to Oklahoma and from Illinois to Nebraska. The Prairie Network is laid out in a geometric system of equilateral triangles, with a camera station at the apex of each triangle. Adjacent stations are approximately 160 miles apart to provide maximum field coverage and overlap and to increase the possibility of simultaneous observations by two or more stations.

4.3 Baker-Nunn Camera

The Baker-Nunn camera used at the 12 SAO field stations is a modified Super-Schmidt F/1 system. The camera photographs a sky field of 30° × 5° and can record satellites down to +13.5 magnitude against a reference star background. The camera is designed to track satellites of any inclination and angular velocity. Time to a fraction of a millisecond is recorded on film automatically.

4.4 Comparison of Field Capabilities

Tests have been conducted comparing Moonwatch optical observations with Baker-Nunn photographic satellite observations that were both precisely reduced (photoreduced) and field-reduced. The comparisons were made on the basis of orbits derived from photoreduced observations, so that the approximate error of field-reduced and optical observations could be determined. The criteria for determining residuals on optical observations were the same as for determining residuals on photographic field-reduced observations.

A review of the capabilities of Moonwatch optical observers revealed that one-third of all observers achieve standard deviations (derived from residuals on all satellites observed for a period of 1 year) with an accuracy that permits their observations to be specially selected for research applications. Of this group, approximately 26 observers have standard deviations lower than that assigned to photographic field-reduced observations, while some observers routinely achieve standard deviations less than half that of photographic field-reduced observations.

4.5 Communications

SAO has a fully staffed communications division equipped for sending and receiving messages around the world via teletype or telephone. In addition, Moonwatch maintains amateur radio links between SAO Headquarters and hard-to-reach stations. Because conventional communications are difficult with stations in Argentina, a regular twice-weekly schedule was implemented for transmitting satellite ephemerides and resulting observations between Headquarters and Argentina stations. Further, a special amateur radio link covering Apollo and other space missions of special interest is operational within the United States.

Direct communication is maintained by radio with the dispatch offices of all participating VFON airlines. Flight officers anywhere in the world can be reached while in flight in real time; in this way, they can be alerted of an impending decay or possibly hazardous reentry event that might occur near or over their flight path.

All VFON communications, including satellite-decay predictions and returned observations, are handled for Moonwatch by Aeronautical Radio Inc. of Annapolis, Maryland, through their international commercial-airline radio network.

5. PREDICTING SATELLITE ORBITS AND REENTRY

5.1 Factors Affecting Satellite Orbits

From the moment a satellite achieves orbit, its orbit begins to degrade. Whether it will complete millions of revolutions around the earth or only a few depends on its apogee and perigee heights and its period. The multiplicity of orbital parameters belonging to a particular satellite, as well as air drag, solar radiation pressure, and gravitational perturbation effects, complicates the procedure for predicting precisely when a satellite will pass through a given point in its orbit.

Within the period of this grant, SAO scientists have continually developed and improved working profiles of the various layers of the lower, middle, and upper atmosphere through analyses of the effects of atmospheric drag on satellite orbits. The satellites used encompass a varied range of area-to-mass ratios and represent a comprehensive assortment of orbital parameters. Both satellite observational data and meteor observational data, primarily supplied by the Prairie Network, have been instrumental in providing information on the structure and details of atmospheric variations.

For a satellite with a relatively high perigee and a small area-to-mass ratio — i.e., a satellite with a long lifetime — the structure in the earth's gravitational field largely determines the variations in its orbit. As these terms are now well known, the predicting of long-term orbital elements is feasible. However, for satellites with large area-to-mass ratios (for example, rocket bodies or balloons) and relatively low perigee heights, the perturbations due to air drag and solar radiation pressure have more effect on the satellite's orbit. Indeed, the effects of solar radiation pressure can become more important than those of air drag for certain satellites in eccentric orbits with apogee heights over 2000 km.

Orbit prediction becomes even more complicated when the sum total of observations made on a satellite covers only a small segment of its orbit. Often the tracking coverage of a satellite represents only 10 to 20% of the orbit. Fortunately, in many cases, the availability of Moonwatch observations has substantially enlarged this coverage. The geographical extent of Moonwatch stations throughout the term of this grant has constantly increased.

5.2 Factors Affecting Satellite Decay and Reentry

Even though orbit predictions can now be satisfactorily derived for satellites to be tracked for a long period of time, the most critical part of a satellite's lifetime is the final 48 hours before reentry. Decay predictions are most difficult during this period.

The predicting of satellite orbits near decay begins when perigee drops below a height of about 180 km. This phase generally lasts only a few days, with the orbit becoming, in most cases, nearly circular. The effects of atmospheric drag become increasingly pronounced, with the result that predictions are even more difficult to calculate. In the last few hours of a satellite's lifetime, the orbital elements change at an ever accelerating pace. Therefore, continual updating of information is required to determine with accuracy the entry and possible impact point.

Characteristics of the final reentry of a satellite are determined by the structure of the atmosphere at that time, the body's ballistic coefficient, and the eccentricity and orientation of its orbit. Unfortunately, simple extrapolation of satellite altitude versus time — even considering variations of atmospheric density — will not produce predictions of the desired accuracy. Even slight changes in initial eccentricity can cause appreciable changes in orbital lifetime. Furthermore, a "given" lifetime can result from any of several combinations of eccentricity and ballistic coefficient.

Obviously, the point at which a satellite begins its final spiral descent is critically dependent both on the satellite's ballistic coefficient and on the density of the atmosphere along the orbit at that particular time. A small change in either of these factors can result in a miscalculation of about half a revolution, that is, ±44 minutes of orbital lifetime. Therefore, the question of where impact might occur depends both on precise values of the orbital elements just before decay and on the state of the atmosphere. Considering the sensitivity of a satellite's lifetime to eccentricity and ballistic coefficient, predictions of impact location and time can represent only a probability estimate,

5.3 Computer Programs for Decay and Orbit Predictions

From a model atmosphere developed by Smithsonian scientists, a computer program was written for predicting satellite decay. This program, SLAVE, is also used by the atmospheric group as an interpolation and fitting device, as well as in studies of atmospheric densities, rotations, and similar matters. The program is based on a numerical integration of the equations of motion in Lagrangian form. Because it stems from an analytical formulation of the equations of motion rather than from numerical integration, the program is more rapid than the usual orbital ephemeris programs. Included in the program are secular and long-period gravitational perturbations, air-drag perturbations, and perturbations due both to direct solar radiation pressure and to the pressure of reflected and reemitted radiation from the earth.

Another computer program developed for orbit updating based on Moonwatch and other observations was the Differential Orbit Improvement (DOI) program. Using the latest observational data from a variety of sensors, DOI weighs them according to a predetermined standard, compares them with each other, and, taking a variety of parameters into account, derives a new, updated orbit. Fundamental design characteristics incorporated with the DOI include atmospheric-drag effects, numerous gravitational effects, solar radiation pressure, and lunisolar perturbations.

5.4 Observing Satellites at Great Distances

As Moonwatch developed and more and more predictions and observations were made, problems were encountered in observing artificial satellites at great distances from the earth. When such distant, very faint, high-apogee satellites are at or near apogee, their motion matches or nearly matches stellar diurnal motion, making identification very difficult. A network within Moonwatch was formed specifically to observe these distant satellites. A special computer prediction program was designed, and selected experienced observers were trained in the new techniques. Large observatory-type telescopes were necessary for reaching these satellites, which at times were of less than 14th magnitude.

6. PROGRAM RESULTS

During the course of this grant, data derived from Moonwatch Network observations have been utilized for improving the computation of predictions for satellites as they near decay and for predicting the time and place of decay. Observational data received from the Moonwatch Network contribute substantially to routine orbit updating and maintenance, not only for the DOI program, but also for many other on-going research projects.

At times, Moonwatch has been the only source of observations available for orbit information. This happens, for example, when poor weather or limited visibility prevents the Baker-Nunn network from making sufficient observations. In many cases, the much denser concentration of Moonwatch stations has enabled better coverage.

In addition to routine observations, Moonwatch has also provided data on satellites whose orbits are used for upper atmospheric and geopotential harmonic studies, as well as on Smithsonian Responsibility satellites (i.e., satellites assigned by NORAD to the SAO Baker-Nunn network) when they are out of the visibility ranges of the cameras. Satellites in highly elliptical orbits, with apogees between 35,000 and 45,000 km, are also tracked. Moonwatch observers have helped establish orbits for newly launched satellites, including multiple launches and breakup, and have assisted in gathering observational data on satellite decays and impacts, searches for lost satellites, and special space tests. Many of the observations performed over the years have been helpful in such areas as establishing the position, expansion rate, and magnitude of atmospheric tests and barium ion tests.

Throughout the term of this grant, members of SAO and Moonwatch have viewed and recorded numerous satellite decays. Some of them are spectacular events observed by many people over half a continent; others are hardly noticed, except by alerted Moonwatch observers. Many of these reentry events have been described, photographed, and sketched, and they are usually recorded in the Moonwatch Newsletter.

Moonwatchers have also covered all Apollo missions; their observations of the manned vehicles and images have been video-taped out to distances of 200,000 statute miles. Coverage of the Apollo spacecraft includes earth orbit, translunar injection, coast to the moon, return to earth, and atmospheric entry of the command module. Ephemerides for Apollo 14, for example, were calculated and distributed to nearly 300 observers around the world. Data from the resulting observations were used by researchers to help resolve questions of contamination by cryogenic and other ventings of the spacecraft, as well as of the physical appearance and behavior of a spacecraft as it begins to enter and traverse the burning period of reentry.

Moonwatchers have also provided many observations of meteors and fireballs over the years to the American Meteor Society for their work on computing meteor orbits and paths.

A few pieces of purported satellite debris from different parts of the world have been sent via the Moonwatch network to SAO for analysis; none of these, however, proved to be remnants of space objects, except for the Manitowoc fragment.

The special network established within Moonwatch to observe far-distant satellites has been most successful, with observations now made on a regular basis. Observers using telescopes up to 30 inches in diameter, some with image intensifiers, have been especially active. The success of Moonwatch in this area of satellite tracking is best demonstrated by the recovery of a "lost" high-apogee satellite. After NORAD was unable to observe the object with any optical, photographic, or electronic sensor for over 6 months, Moonwatch was requested to aid in the search. From the old elements, an updated set of elements was calculated that enabled the object to be sought, recovered, and observed all within less than 10 days.

Over the years, VFON members have reported numerous satellite decays from predictions and alerts that were specially prepared for in-flight use. In many instances, pilot reports of satellite decays have been the only ones received by Moonwatch and the Space Defense Center. Although air-borne observers can relate a satellite-reentry trajectory and appearance only to their own position in flight, they have the advantages of being over parts of the earth where ground stations are not possible and of usually being above obscuring clouds.

In addition to reporting satellite decays to Moonwatch, pilots have observed thousands of meteors and fireballs, atmospheric tests, reentries of manned space capsules, forest fires, oil spills, bird migrations, hurricanes, volcano eruptions, islands appearing and disappearing, and other environmental events. Moonwatch Headquarters distributes this information to scientists and agencies engaged in those particular studies.

During the 6-year period of the grant, the Moonwatch Division of SAO has made more than 300,000 satellite observations. Some 175,000 of these are positional in nature and are essentially used for defining density profiles of the atmosphere, rotation of the atmosphere, and gravity anomalies. The remaining observations are optical signature, from which is derived a better understanding of the effects the above factors have on changes in satellite orientation in space, changes in tumble rate, and changes of albedo.

At the request of the United Kingdom and NASA project managers, Moonwatch helped determine the spin-axis attitude of Ariel 3 to within ±5°. Observations over a 21-month period proved that attitude determinations to accuracies of ±2° could be accomplished.

Within the total grant period, 2500 satellite pieces decayed in the earth's atmosphere. Of them, nearly 700 major pieces — for example, satellite payloads, rocket stages, platforms — were assigned to Moonwatchers. Working closely with NORAD's Space Defense Center, Moonwatch calculated reentries and prepared look-angle predictions on these "primary" pieces of space debris; resulting data were phoned, telegraphed, or radioed to all satellite observing stations of the world having possible visibilities.

Over 20,000 positional and almost 18,000 optical-signature observations were made in the final 8-month period, during which time, 202 satellites decayed. NORAD prepared tracking and impact predictions for 68 of these decays, and Moonwatch calculated and telegraphed relevant data to appropriate stations.

7. CONCLUSIONS

Current knowledge of the dynamics of the earth and the atmosphere, and of the effects of solar and lunar perturbations on orbiting satellites, appears sufficient to provide generally accurate predictions of satellite decay and reentry. However, despite great improvements in the accuracies of predicting long-term satellite decay, the final predicted "decay window" still appears to have an uncertainty of approximately 10% of a satellite's remaining lifetime. In other words, predictions of 30-day lifetimes are accurate only to about 3 days; 10-day lifetimes, to about 1 day; and so on. Of course, some decay predictions will be much more accurate than this; conversely, the uncertainty can vary by 50% or more, even within a few hours of reentry.

Why is there a need for greater precision in decay prediction? An uncertainty of 1 hour some 10 hours before a predicted decay represents approximately two-thirds of a satellite orbital revolution, which, of course, may cover densely inhabited areas of the earth as well as oceans and wastelands. This consideration becomes more critical in light of annual increases in both the frequency of launchings and the weight of space payloads, as well as the increasing concentrations of people in urban centers and the potential growing number (and size) of aircraft flying at supersonic speeds and at altitudes nearly double those being used by present aircraft.

To improve the accuracy of predictions, intensive atmospheric research must be devoted to understanding the critical altitudes between 150 and 200 km; for this, simulation models should be developed to represent any period in the solar cycle for any year, hour, latitude, or longitude. Coupled with final in-orbit parameters of the satellite and its ballistic coefficient, this information could permit a substantially higher accuracy plateau for decay predictions.

It is also hoped that future consideration can be given to expanded efforts for observing near-earth and reentering satellites with advanced optical, photographic, and electronic facilities over much greater areas of the earth.

Although one of the primary objectives of the Study of the Decay and Recovery of Orbiting Artificial Space Objects — namely, to recover and analyze reentry debris — was not met, many of the secondary objectives indeed were. More than 700 decaying objects were tracked by Moonwatchers, and the volume of their observations led to many refinements in predicting methods. Data supplied by the Moonwatch Network, in combination with Baker-Nunn observations, were instrumental in defining the factors affecting satellite decay and, hence, in enabling more precise predictions to be made of reentering objects.

NASA Grant NGR 09-015-007 enabled Moonwatch to participate and substantially contribute to every phase of satellite tracking throughout the United States and the world. In the course of directing and coordinating worldwide volunteer satellite tracking, Moonwatch guided the beginning steps of many entrants in the field of space science. Further, during these years, Moonwatch provided NASA with a public-relations vehicle that informed and created public interest in NASA's accomplishments and future objectives for space programs.